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A METHOD FOR THE CALCULATION OF
PARACHUTE OPENING FORCES FOR HIGH
ALTITUDE BALLOON PAYLOADS

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7 May 1975

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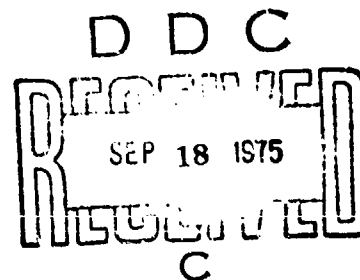


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PETER L. MILLER, Jr, Capt, USAF

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A Method for the Calculation of Parachute Opening Forces for High Altitude Balloon Payloads

1. INTRODUCTION

Each year a large number of valuable scientific payloads are committed to flight on high altitude balloons. In general the balloons ascend into the stratosphere. They have gone as high as 170,000 ft MSL (mean sea level) and often have flight durations of several days. At the conclusion of the flight the payloads are usually recovered by means of a parachute system for later reuse. The parachute apex is attached to the bottom end fitting of the balloon and flown unpacked in line with the payload suspended below. At the conclusion of the balloon flight the parachute is separated from the balloon and descends with the payload to the ground.

One of the questions most frequently asked by the scientists/experimenters who design the payloads and interpret the data obtained concerns the magnitude of the parachute opening force. Conventional methods for deriving parachute performance parameters in the dense lower atmosphere do not reliably predict this information for the parachute released in the very high altitude environment. An analytical answer to the question is sought. Existing theory and an analytical method recently developed by Ludtke¹ for horizontal deployment is adapted to the balloon system requirements. Engineering methods are used to develop expressions which allow the assessment of the parachute opening forces.

(Received for publication 7 May 1975)

1. Ludtke, W.P. (1972) A Technique for the Calculation of the Opening-Shock Forces for Several Types of Solid Cloth Parachutes, NOLTR 72-146.

2. OPENING DYNAMICS

At the termination of the flight when the apex of the parachute system is separated from the balloon, the parachute/payload system begins to free fall. The strain energy, which had been stored in the parachute suspension lines, risers, and canopy when the system was supported by the balloon, causes the parachute to be accelerated towards the payload. As the system descent velocity increases a few parachute gores which may begin to catch air and/or skin drag on the canopy tend to stretch the system back into line. The payload will see a momentary force peak as the system snaps back into tension. This "snatch" force is generally taken to be the beginning of parachute filling.

The further motion of the descending system can then be described by Newton's second law of motion.

$$\Sigma F = ma ,$$

$$W - \frac{1}{2} \rho v^2 C_D S = \frac{W}{g} \frac{dv}{dt} . \quad (1)$$

Integration of Eq. (1) requires a knowledge of the change of air density (ρ) with time and of the change of drag area ($C_D S$) with time. Let it be assumed that during the opening period the atmospheric density can be represented by

$$\rho = a_1 e^{a_2 z} , \quad (2)$$

where a_1 and a_2 are constants and z is altitude MSL. Then altitude at any instant may be determined from

$$\frac{dz}{dt} = v(t) . \quad (3)$$

3. LUDTKE'S TECHNIQUE

3.1 Opening Force Ratio

Ludtke¹ has suggested that parachute opening can be considered with respect to a reference opening time, t_o . This reference time is the instant when the canopy is considered to have just achieved its fully inflated steady-state diameter and volume for the first time. Additional inflation beyond the reference time is considered to be caused by the elongation of the canopy materials under the applied loads. For purposes of curve fitting the reference time (t_o) was established as

the first point on the infinite mass wind tunnel force-time plot where the instantaneous force (F) was equal to the steady-state drag force (F_s).

$$F = \frac{1}{2} \rho v^2 C_D S .$$

$$F_s = \frac{1}{2} \rho v_s^2 C_D S_o .$$

For infinite mass conditions where ρ is constant and $v = v_s$ it was determined that

$$\frac{F}{F_s} = \frac{C_L S}{C_D S_o} = R = \left(\frac{t}{t_o} \right)^6 . \quad (4)$$

for most solid parachutes.

Furthermore, all parachutes have some initial drag area at line stretch ($v = v_s$). Therefore it is suggested that

$$R(\eta) = \left[(1-\eta) \left(\frac{t}{t_o} \right)^3 + \eta \right]^2 . \quad (5)$$

where η is defined as the ratio of the projected mouth diameter (D_M) at line stretch to the steady-state frontal diameter (D_{Mo}). Expanding Eq. (5)

$$R(\eta) = (1-\eta)^2 \left(\frac{t}{t_o} \right)^6 + 2\eta(1-\eta) \left(\frac{t}{t_o} \right)^3 + \eta^2 . \quad (6)$$

This expression has been shown to be valid for the finite mass case as well^{1, 2}.

3.2 Determination of Reference Time

At any given time during the parachute inflation the parachute drag force is proportional to the square of the maximum inflated diameter. Using this observation the following assumptions can be made.

(a) The ratio of the instantaneous mouth inlet area (A_M) to the steady-state, fully inflated mouth area (A_{Mo}) is in the same proportion as the instantaneous drag area ratio.

$$\frac{A_M}{A_{Mo}} = R(\eta) . \quad (7)$$

2. Berndt, R.J., and DeWesse, J.H. (1966) Filling time prediction approach for solid cloth type parachute canopies, AIAA Aerodynamic Deceleration Systems Conference, Houston, Texas.

(b) The ratio of the instantaneous pressurized cloth surface (A_S) to the canopy surface area (A_{So}) is in the same proportion as the instantaneous drag area ratio.

$$\frac{A_S}{A_{So}} = R(\eta) . \quad (8)$$

(c) The rest of the canopy is assumed to be unpressurized and therefore has no net air flow.

Applying the principle of conservation of mass

$$dm = m_{in} - m_{out} .$$

$$\rho \frac{dV}{dt} = \rho v A_{Mo} R(\eta) - \rho A_{So} R(\eta) k \left(\frac{C_P \rho}{2} \right)^n v^{2n} , \quad (9)$$

where V is the instantaneous volume of air captured by the parachute and k , n , and C_P are coefficients which are a function of the canopy cloth permeability. A more detailed explanation of these coefficients may be found in reference 1.

4. CALCULATION OF REFERENCE TIME

Parachute opening data suggests that the initial effective diameter ratios used in Eqs. (7) and (8) may not be the same as the initial drag area ratio. Equations (7) and (8) then become

$$\frac{A_M}{A_{Mo}} = R(\eta_M) \quad (10)$$

and

$$\frac{A_S}{A_{So}} = R(\eta_S) . \quad (11)$$

Equation (9) then becomes

$$\rho \frac{dV}{dt} = \rho v A_{Mo} R(\eta_M) - \rho A_{So} R(\eta_S) k \left(\frac{C_P \rho}{2} \right)^n v^{2n} . \quad (12)$$

The reference time may now be calculated by making an initial guess for t_0 and numerically integrating Eqs. (1), (3), and (12) simultaneously from $t = 0$ and $V = 0$ to $V = V_0$. The quantity V_0 is the known steady state parachute volume which may be determined as shown in reference 3. Then the time $V = V_0$ is a new estimate for t_0 and the equations can again be integrated to obtain a new estimate for t_0 . This process will converge to t_0 .

5. END POINT DETERMINATION

Once the parachute reaches its nominal shape it continues to increase in area according to Eq. (4). This inflation process is limited by the loads applied to the canopy, the elasticity of the canopy, and its constructed strength (F_c). A linear load elongation relationship is used to determine the maximum drag area at any time.

$$\frac{\epsilon}{F} = \frac{\epsilon_{\max}}{F_c} \quad (13)$$

where ϵ_{\max} is the strain of the parachute material when loaded to its constructed strength (F_c). At any time the force (F) on the parachute is given by the drag.

$$F = \frac{1}{2} \rho R(\eta) C_D S_0 v^2 \quad (14)$$

In steady descent the applied load is just the system weight (W) and the parachute drag area is increased by the factor

$$\left(1 + \frac{W \epsilon_{\max}}{F_c} \right)^2$$

However, it must be recalled that parachute drag coefficients are usually determined using the parachute nominal drag area. Therefore, at any given time the drag area ratio is limited to

3. Ludke, W. P. (1970) A New Approach to the Determination of the Steady-State Inflated Shape and Included Volume of Several Parachute Types in 24-Gore and 30-Gore Configurations, NOLTR 70-178.

$$R = \left(\frac{1 + \frac{F_{\epsilon \max}}{F_c}}{1 + \frac{W_{\epsilon \max}}{F_c}} \right)^2 \quad (15)$$

The drag area ratio of a parachute thus initially increases according to Eq. (6) until $t = t_o$ and then according to Eq. (4). The increase in drag area ratio is limited to the value given by Eq. (15) at any instant of time. The calculation of the limiting drag area ratio, therefore, requires the simultaneous solution of Eqs. (14) and (15).

6. APPLICATIONS

In order to evaluate the behavior of these equations a computer program was written to numerically integrate the equations as a function of time. Table 1 shows the input parameters required for a 135-ft diameter flat circular parachute. Figures 1 through 5 show the force, velocity, and drag area ratio as a function of time for the 135-ft parachute opening at a snatch velocity (v_s) of 160 ft/sec in vertical deployment at several snatch altitudes. It can be observed that the system velocity increases after snatch until the drag force exceeds the system weight. The maximum force (F_{\max}) occurs well before the parachute is fully open at low altitudes. At 1000 ft MSL, F_{\max} occurs when the drag area is only 10 percent of

Table 1. Input Parameters for 135-ft Parachute

D_o	135 ft
W	10,000 lbf
C_D	1.22
V_o	290,000 ft ³
F_c	88,000 lbf
ϵ_{\max}	0.30
η_S	0.02
η_M	0.02
D_{Mo}/D_o	0.674
C_P	1.15
k	1.46042
n	0.63246

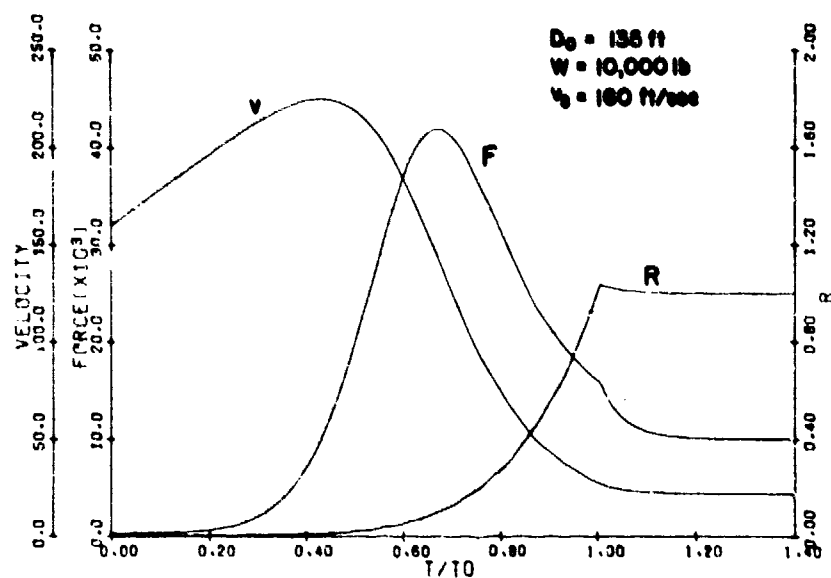


Figure 1. Opening of a 135-ft Diameter Parachute at 1000 ft MSL

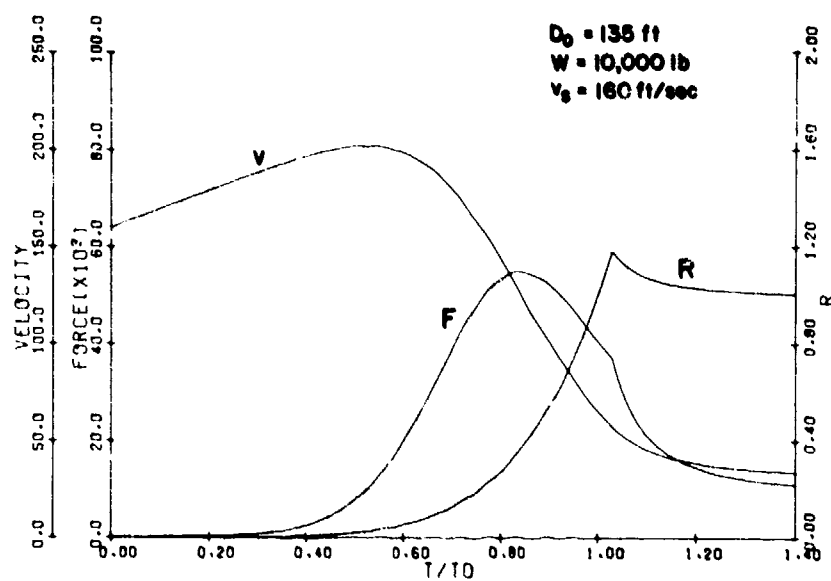


Figure 2. Opening of a 135-ft Diameter Parachute at 25000 ft MSL

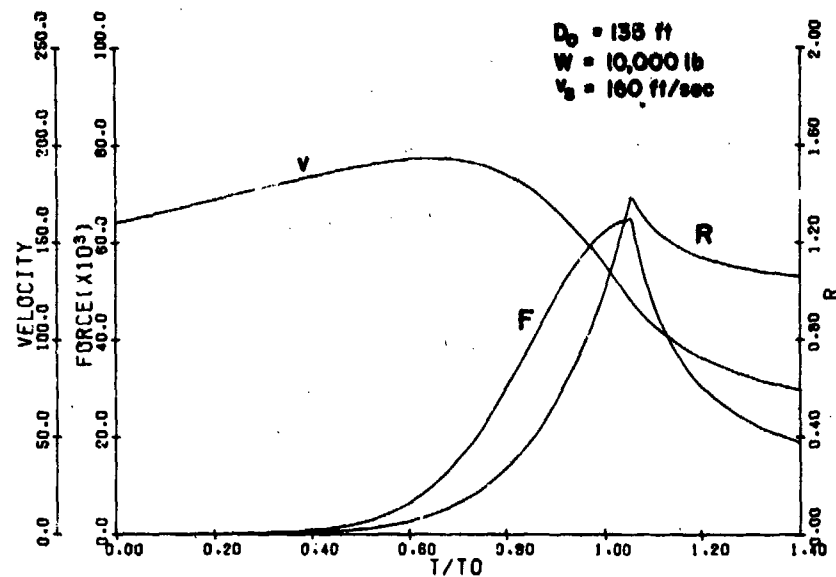


Figure 3. Opening of a 135-ft Diameter Parachute at 50000 ft MSL

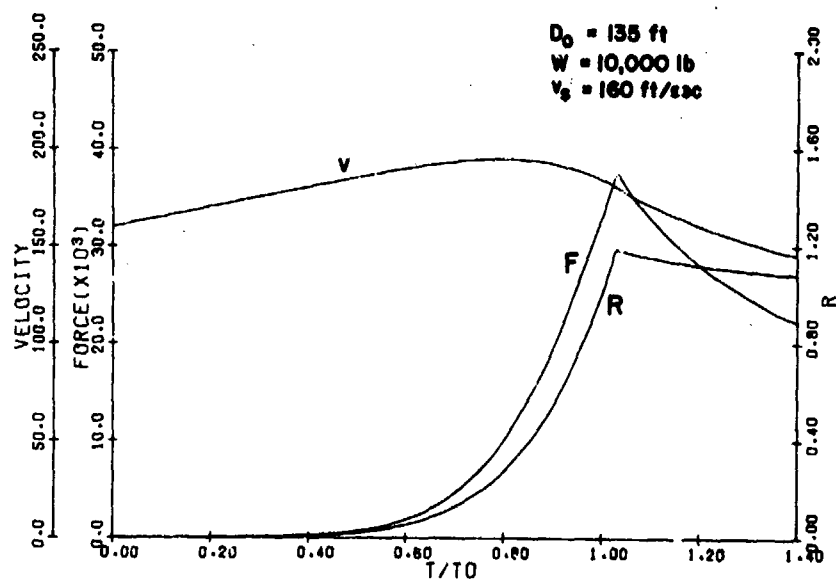


Figure 4. Opening of a 135-ft Diameter Parachute at 75000 ft MSL

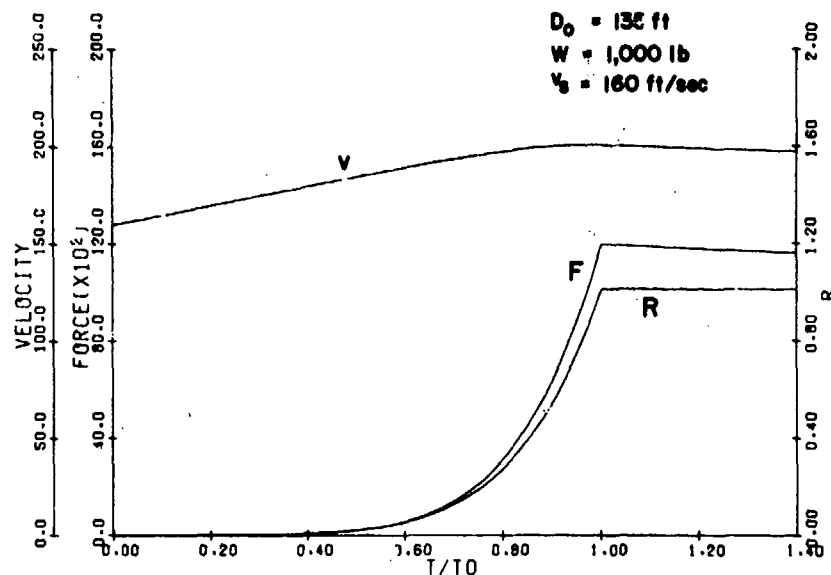


Figure 5. Opening of a 135-ft Diameter Parachute at 100000 ft MSL

of the nominal drag area. As the snatch altitude is increased, however, the time of maximum force occurrence becomes later and is after the reference time (t_0) at the higher altitudes.

Figure 6 illustrates that for the 135-ft parachute the reference filling time (t_0) decreases with increasing altitude. Above approximately 60,000 ft MSL the filling time is essentially constant.

In Figure 7 the maximum forces calculated during opening of the 135-ft parachute in the vertical and horizontal modes are compared. The difference between the modes of deployment may be partially explained by the fact that at the end of the opening calculation ($t \gg t_0$) the drag force tends towards W for the vertical deployment. The maximum opening force as a function of altitude has a peak at approximately 55,000 ft. The maximum force is limited by the maximum drag area and velocity experienced. In horizontal deployment the maximum drag force is approximately F_s , which is the force that would be experienced by the fully open parachute at v_s . For vertical deployment F_{\max} exceeds F_s , due to the increase in velocity after snatch. The maximum force in horizontal or vertical deployment may also exceed F_s due to stretching of the parachute ($R > 1$).

As a second example consider the input parameters shown in Table 2 for a 35-ft parachute. Figures 8 and 9 show F_{\max} for the opening of the 35-ft parachute in horizontal deployment assuming a constant initial velocity ($v_s = 400 \text{ ft/sec}$)

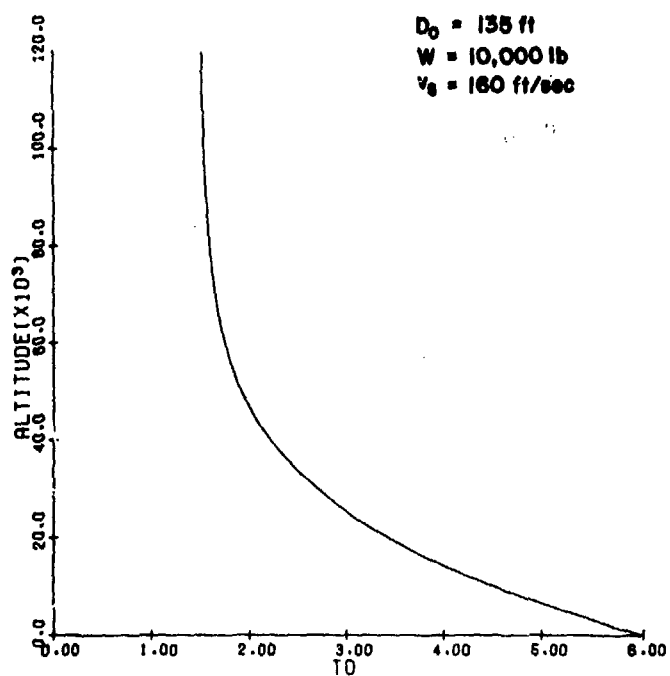


Figure 6. Release Time (t_0) as a Function of Altitude for a 135-ft Diameter Parachute

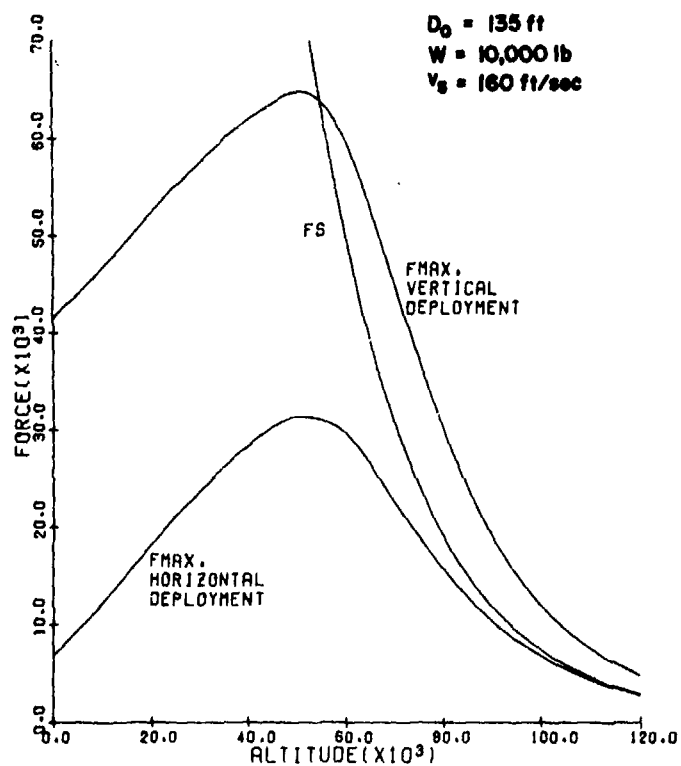


Figure 7. Maximum Opening Force for a 35-ft Diameter Parachute in Horizontal Deployment

Table 2. Input Parameters for 35-ft Parachute

D_o	35 ft
W	200 lbf
C_D	0.70
V_c	4315 ft ³
F_c	11250 lbf
ϵ_{max}	0.32
η_S	0.0
η_M	0.0
D_{Mo}/D_o	0.66
C_P	1.15
k	1.46042
n	0.63246

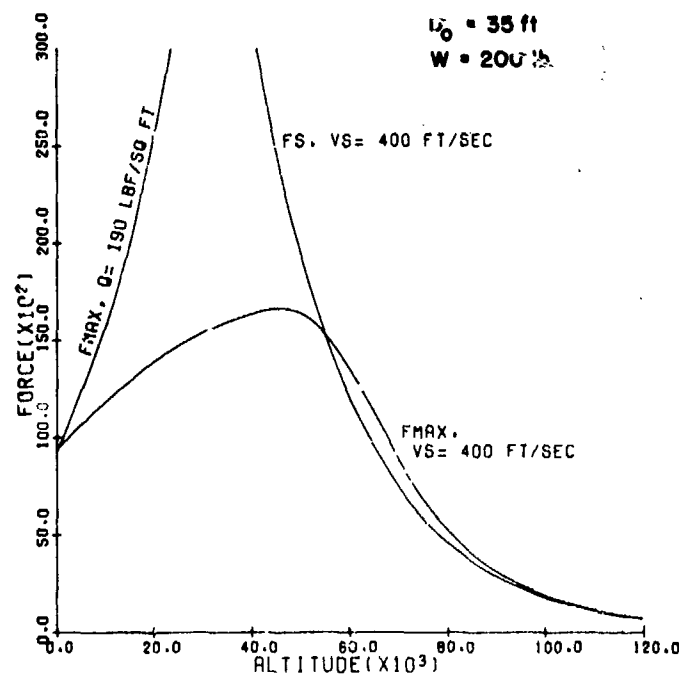


Figure 8. Maximum Opening Force for a 35-ft Diameter Parachute in Horizontal Deployment

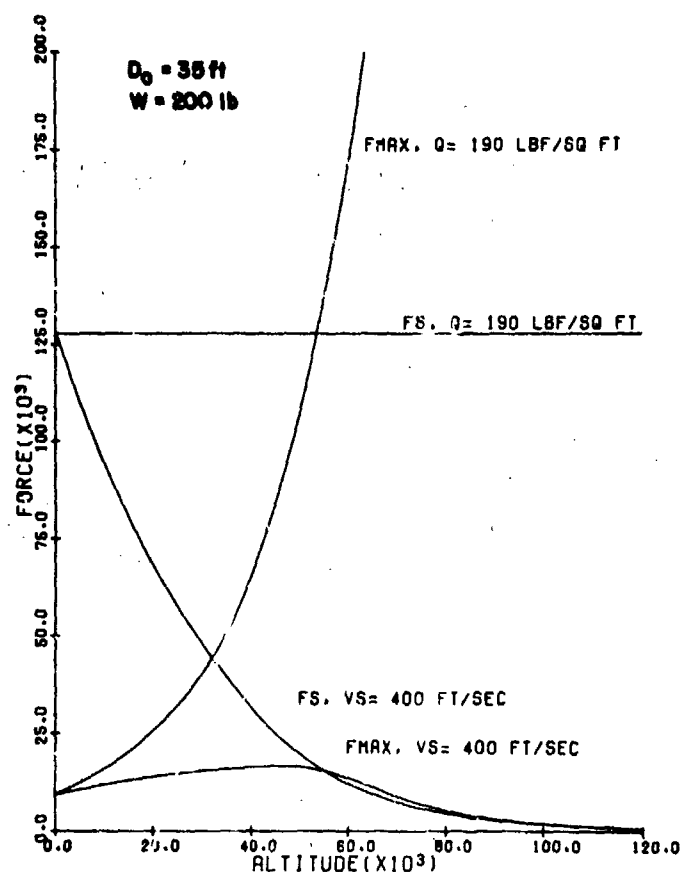


Figure 9. Maximum Open Force for a 35-ft Diameter Parachute in Horizontal Deployment

and a constant initial dynamic pressure ($q = 190 \text{ lbf/ft}^2$). Note that F_{max} exceeds F_s for the $v_s = 400 \text{ ft/sec}$ case due to the straining induced in the parachute canopy. Also note that the maximum force for the $q = 190 \text{ lbf/ft}^2$ example continues to increase with altitude and is in agreement with the trends discussed elsewhere in the literature.⁴

A number of cases were evaluated at different initial velocities and altitudes for the 135-ft parachute and are plotted in Figure 10. The maximum spread in the F_{max} data occurs in the region of maximum value. If the data of Figure 10 are replotted, using a free fall time (t_s) to calculate v_s , then the result is as shown in Figure 11.

4. Performance of Design Criteria for Deployable Aerodynamic Decelerators, (1963) TR ASK-TR-61-579, AFFDL, AFSC.

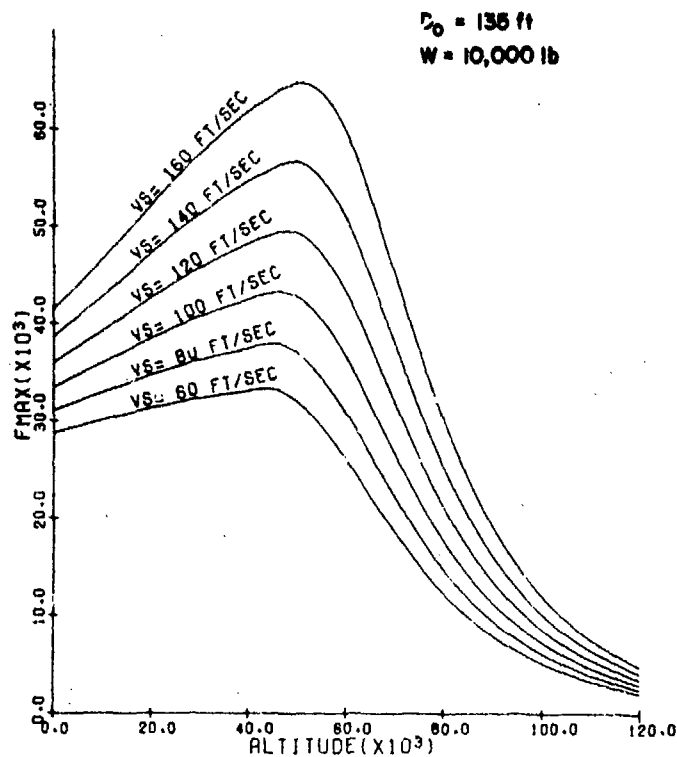


Figure 10. Maximum Opening Force for a 135-ft Diameter Parachute as a Function of Snatch Velocity and Altitude in Vertical Deployment

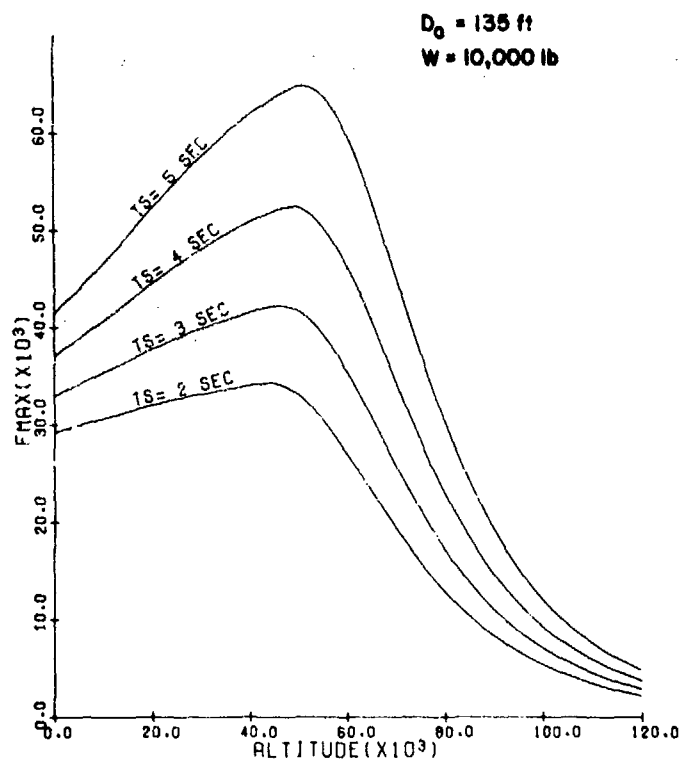


Figure 11. Maximum Opening Force for a 135-ft Diameter Parachute as a Function of Snatch Time and Altitude in Vertical Deployment

7. CONCLUSIONS

If it can be assumed that the snatch force will occur at a relatively constant time after separation from the balloon then the plot of Figure 11 shows that it would be better to terminate the mission at higher altitudes rather than at lower altitudes. Although it is not known whether the snatch time (t_g) is constant with altitude, it is known, in general, to be less than 5 sec based on limited flight data at altitudes above approximately 50,000 ft MSL.

No attempt is made to quantitatively prove or disprove the validity of the mathematical model herein discussed. It does qualitatively agree with experience and its quantitative results are a function of the input parameters, which may not all be well known. However, the trend analysis provided by the type of plot shown in Figures 10 and 11 is useful for high altitude balloon mission planning.

Symbols

A_S	Instantaneous pressurized canopy surface area, ft^2
A_{So}	Steady-state inflated canopy surface area, ft^2
A_M	Instantaneous canopy mouth area, ft^2
A_{Mo}	Steady-state inflated mouth area, ft^2
a	Acceleration, ft/sec^2
a_1, a_2	Constants, Eq. (2)
C_D	Parachute coefficient of drag
C_P	Parachute pressure coefficient; relates internal and external pressure (P) on canopy surface to the dynamic pressure of the free stream
C_D^S	Instantaneous drag area, ft^2
C_D^{So}	Steady-state drag area, ft^2
D_M	Instantaneous diameter of the mouth of the canopy, ft
D_{Mo}	Steady-state inflated mouth diameter, ft
D_o	Nominal parachute diameter, ft
F	Instantaneous force, lbf
F_c	Constructed strength of the parachute, lbf
F_{max}	Maximum opening-shock force, lbf

F_s	Steady-state drag force that would be produced by the fully open parachute at v_s , lbf
g	Gravitational acceleration, ft/sec ²
k	Permeability constant of canopy cloth
m	Mass, slugs
n	Permeability constant of canopy cloth
q	Dynamic pressure, lbf/ft ²
R	Ratio of instantaneous drag area to nominal drag area ($C_D S_0$)
S	Instantaneous inflated canopy surface area, ft ²
S_0	Canopy surface area, ft ²
t	Instantaneous time, sec
t_0	Reference time when the inflating parachute has reached the design drag area for the first time, sec
t_s	Fall time before snatch, sec
V	Instantaneous volume of air collected by canopy, ft ³
V_0	Total volume of air which must be collected during the inflation process, ft ³
v	Instantaneous system velocity, ft/sec
v_s	Snatch velocity, ft/sec
W	System weight, lb
z	Altitude, ft MSL
ϵ	Instantaneous strain
ϵ_{max}	Maximum strain
η	Ratio of parachute projected mouth diameter at line stretch to the steady-state inflated mouth diameter
η_M	Ratio of initial mouth diameter to steady-state inflated mouth diameter
η_S	Ratio of initial effective pressurized cloth diameter to canopy nominal diameter
ρ	Air density, slugs/ft ³